AIRBORNE SEPARATION ASSURANCE VALIDATION WITH MULTIPLE HUMANS-IN-THE-LOOP

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Abstract

This paper describes two experiments, in which multiple humans controlled a large number of aircraft in a simulation of a Free Flight environment. The high number of human-human conflicts allows the investigation of the effect of human interaction on micro-scale and on the traffic pattern. The results have also been used to compare the behaviour of the pilot models in the traffic simulation with the real pilot's behaviour. For these experiments a network of PC-based flight simulators has been used using pilots world-wide via the internet, but also in a classroom environment. The results indicate that human pilots behave very similarly to the pilot models. Because of anticipating behaviour humans are better at avoiding peak conflict rates in complex conflict geometries.

Introduction

Free Flight is an Air Traffic Management (ATM) concept based on allowing self-optimisation by the airspace users as much as possible. A critical element of this concept is airborne separation assurance [1,2]. In Free Flight airspace the separation assurance task and responsibility has been moved from a ground-based controller to the cockpit crew, assisted by an airborne separation assurance system (ASAS). How and when this responsibility should be moved to the cockpit is the subject of ongoing research.

Applying airborne separation assurance changes the ATM system from a centrally organised system to a distributed system. This decentralisation results in a more robust system [3]. For the capacity of upper airspace, the limiting factor changes from controller workload to pilot workload and the probability of bottleneck traffic patterns due the lack of central control.

In co-operation with NASA, the FAA and the RLD, NLR has investigated the feasibility of Free Flight in upper airspace for a number of years [4]. The project follows a requirements based approach: What is minimally required to enable airborne separation assurance, but also what are the benefits? The research is part of the NASA Distributed Air/Ground Traffic Management (DAG-TM) concept validation as defined in the AATT program [5,6].

Data from human factors experiments with NLR's research flight simulator, like pilot workload ratings in high traffic densities, show that airborne separation assurance has the potential to dramatically increase the capacity of upper airspace. Offline traffic simulations confirmed the low individual conflict rate and showed that even bottleneck traffic patterns, as shown in figure 1, solved efficiently without central control.

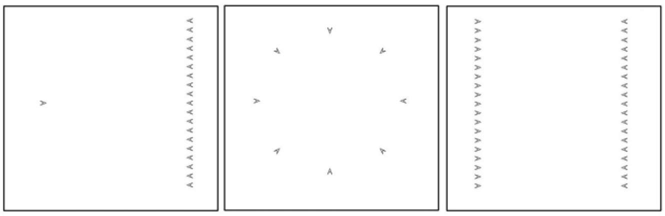

Figure 1 Examples of complex traffic geometries that solved efficiently without central control (from left to right: ‘wall’, ‘superconflict, ‘frontlines’)

Offline traffic simulations were performed using NLR’s Traffic Manager program (TMX). This PC based program can simulate 1000 aircraft of over 200 different types simultaneously including aircraft performance, FMS, pilot reaction times and ASAS. However, the pilot models used in this program are relatively simple and do not feature complex cognitive behaviour. Even though their parameters have been based on the results of the flight simulator trials, this means that the traffic patterns could resolve quite differently with real humans in the loop. It is hard to predict whether this will improve or worsen the way in which the complex multiple-aircraft conflicts are solved.

Research Questions

For the feasibility of Free Flight it is important to know whether and how effectively potential bottleneck traffic patterns will be resolved. The off-line traffic simulations show only that a decentralised system is able to solve these situations without central control. The realism of the simulations should be verified by comparing it with traffic controlled by multiple humans-in-the-loop. The fact that it can be solved does not mean that it will also happen. There might be an effect of the differences between the "bots", as the pilot models are often called, and the humans on the dynamics of the traffic pattern in both normal and extreme traffic situations.

Therefore, the more specific research questions for these experiments were:

- What are the differences between the pilot models (‘bots’) and humans in normal traffic patterns?
- What is the effect of humans in the loop on the dynamics of the complex traffic geometries?

The differences between the humans and bots on an individual scale are not completely unpredictable. Humans are more intelligent and will exhibit more strategic behaviour. Unlike the bots, humans will also show individual differences. For conflict solving the strategic effect can be beneficial. The human might be better at preventing secondary conflicts as a result of conflict resolution manoeuvres. On the other hand the strategic effect could also lead to more competitive behaviour. To optimise individual workload and flight efficiency, a pilot might decide to wait for a while before reacting to a conflict alert at the cost of the overall efficiency. This will clearly deteriorate the way in which the bottleneck conflict is solved. Another effect might be that individual differences hinder the useful wave-like patterns that occur in off-line simulations. The overall outcome depends on which effect will dominate.

Because of the high level of interaction, this question cannot be solved with one or two flight simulators. A high number of human-controlled, simulated aircraft are required. Therefore two experiments have been designed using a simulation configuration with 10-24 humans in the loop.

Web experiment

Goal

The goal of the web experiment was to answer the first research question: What are the differences between the bots and humans in normal traffic patterns?

Method

For this a set-up was used consisting of a distributed simulation network. To have a high number of participants it was chosen not to use high-fidelity moving base research flight simulators, but a much lower fidelity simulator: a PC-based flight simulator featuring EFIS, an autopilot, ASAS but without an FMS (though there was a simulated FMS path on the display system). Much in the same way as internet multi-player games, the Traffic Manager program was extended with the internet game host functionality. By using a specifically designed protocol based on Microsoft DirectX, a user could log onto a traffic scenario running on the Traffic Manager. A system of passwords and session id's allowed the experiment manager control over the selection of participants.

The flight simulation program, called Freesim, (see figure 2) was put on the web to download together with an application form. The Freesim program consists of several components:

- A Fokker 100 non-linear simulation model
- Out-of-the-window view
- Primary Flight Display (PFD) incl. flight mode annunciation, flight director and ASAS indicators
- Navigation Display (ND) incl. profile display and traffic display (CDTI) functions
- Autopilot & Autothrottle system, based on Fokker 100 logic
- Mode control panel, for control of autopilot and autothrottle, no LNAV and VNAV mode
- Display control panel for horizontal and vertical range selections, de-cluttering and clipping
- ADS-B transceiver model including filtering and smoothing
- ASAS system, state-based conflict detection & resolution (CD&R) with conflict prevention (CP)
- Radio (chat) window, mainly for simulation control
- Datalogging (scoring) module

Every Freesim program that was logged in received ADS-B information from all aircraft (bots and pilots) within a range of 100 nm.

A more complete description can be found on the Freesim user manual and download website: http://www.nlr.nl/public/hosted-sites/freeflight/fsmanual/

Figure 2 Freesim flight simulation program

In the experiment there was no ATC assistance for separation assurance. The ASAS system was a state-based, co-operative system based on the modified voltage potential method [7,8]. This conflict resolution method regards the predicted positions at the closest point of approach as two repelling particles in deciding the direction of the manoeuvres. This ensures a co-operative solution without explicit co-ordination or negotiation. The conflict detection uses a lookahead time of five minutes with two urgency levels: amber for a predicted loss of separation between five minutes and three minutes from now and red for a predicted loss of separation within three minutes. On top of the CD&R functionality a so-called predictive ASAS is used as conflict prevention method. By showing red and amber zones on the heading, vertical speed and speed scale, the pilot is informed of which manoeuvres would lead to a conflict alert. This prevents conflicts that would otherwise occur due to the lack of exchanging flight plan information.

The following two traffic rules were prescribed:

1. *As soon as a state-based conflict is predicted within the specified lookahead time, an aircraft should not manoeuvre so as to decrease the distance at the predicted closest point of approach, but resolve the conflict unless a higher priority threat prevents this.* (**conflict resolution rule**)

2. *It is not allowed to initiate a manoeuvre that will result in a state that triggers a state-based conflict alert within the specified lookahead time.* (**conflict prevention rule**)

A score parameter is shown to the pilot to indicate his performance. This was used a driver to ensure appropriate behaviour. Another goal was to introduce a competitive effect. The pilots with the three highest scores were awarded financially.

The score parameter is a rough indication of how the flight is progressing. Flying direct and on schedule at the optimal flight level will increase the score. Penalties were included in the calculation of the score for a number of undesirable actions:

- Leaving the optimal (initial) flight level
- Not flying to the destination (as indicated by the magenta line)
- Not correcting the flight path to ensure the ETA (estimated time of arrival) matches the RTA (required time of arrival).
- Not reacting to conflicts (or late)
- Causing intrusions

Penalties could even lead to a negative score. Not reacting to a conflict to stay at the optimal level clearly leads to a significantly higher penalty than leaving the optimal flight level to solve a conflict. The most beneficial strategy was briefed as:

> *Fly direct, on schedule at the optimal flight level and in case of a conflict solve it as efficient (vertically in most cases) and as quickly as safely possible.*

Other instructions given in the manual:

- Solving conflicts using the vertical speed mode has proven to be the most efficient way in most cases.
- Return to the optimal flight level as soon as the intruding aircraft has been passed.
- The predictive ASAS bands of the conflict prevention system assist in deciding when you can perform the recovery manoeuvre.

Procedures and checklists were also provided on the website.

Data logging consisted of the score parameter as well as, among others, fuel consumption, route-time and number of conflicts. This data was sent periodically to the traffic manager by the Freesim program. The subject also had to fill in a questionnaire about their mental workload and the perceived safety of the flight. They also had to fill in whether they noticed any difference in behaviour of the traffic indicating whether it was a human controlled aircraft or a pilot mode (bot) controlled aircraft.

The subjects could train offline with a few built-in traffic encounters. There was also a number of on-line training days in which participant could log in on the traffic manager 24 hours a day.

The experiment runs were conducted in two sessions of three runs. Each run lasted about 30 minutes.

Despite a call for participation that must have reached at least 3,000 pilots, the resulting number of pilots that participated was surprisingly low. At most 10 pilots participated simultaneously. The reasons for this are unknown but the Freesim program was sensitive to operating system and video card settings. This may have caused some computers to crash, hence resulting in pilots giving up on participating. Another reason may have been the lack of commitment. There was no specific appointment with certain subjects, everybody was free to log in when they had a valid password. This may have caused last-minute decisions to do something else than participating despite the financial reward system.

Results

During the training days only half of the subject pilots ever tried to log in. The lack of a hard training requirement may have decreased the performance of the subjects.

Some participants were late in logging in, others aborted the session during the run. Consequently, a lot of data had to be taken out of the analysis, since they were not collected during a run with at least 20 minutes, which was used as a requirement in the data analysis.

The participants could not distinguish between human controlled traffic and bot controlled traffic. Occasionally pilots thought they were able to tell the difference but proved to be wrong. Someone from the experiment team who flew an observer aircraft was in one occasion able to tell the difference.

After every run the subjects rated the workload of the whole flight in the questionnaire using the workload RSME scale [9]. Contrary to the previous data [8] the average workload rating is relatively high ('rather effortful'). The combination of two effects may have contributed to this: the high traffic density and the low amount of training. More striking is the distribution of the ratings (see figure 3). Even in the same scenario in the same area, the ratings varied from low to high. A few ratings indicate the workload was too high. As a reason for this the conflict rate or multi-aircraft conflicts were mentioned. This indicates that possibly the conflict rate and the conflict complexity are the driving factor for mental workload and not for instance local traffic density. The lack of training may have caused higher workload ratings than measured before in comparable simulator trials.

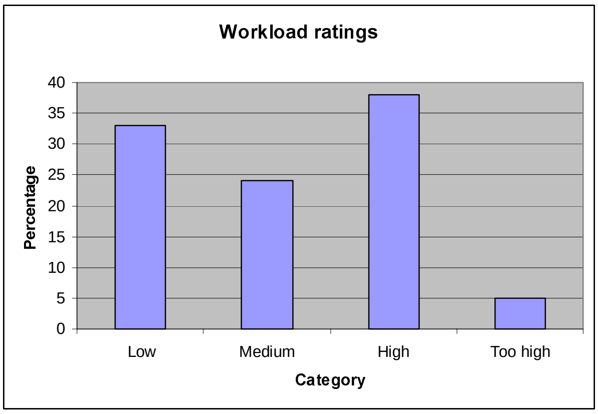

Figure 3 Workload ratings by category (low = 0-33, medium=34-66, high = 67-100, too high = 101-150)

Classroom experiment

Goal

The first goal of this experiment was a validation of ASAS with a high(er) number of human participants. A second goal was comparing the behaviour of the bots with that of human pilots in complex geometries. Thirdly, the effect of different directives, or company strategies, has been compared.

Despite the promising results of the web experiment, there were an insufficient number of valid runs to draw any conclusion on human interaction. The overall number of human-human conflicts was too low. Therefore this experiment was set up with more control over the training and number of participants.

Method

A classroom of the KLM Flight Academy in Eelde was chosen as location. The participants were 24 just or nearly graduated pilots (on average 85 VFR hours, 45 IFR and 37 simulator hours).

A configuration was set-up consisting of 24 PCs with Freesim and three servers (one e-mail server for the questionnaires, one TMX and one back-up TMX server).

Figure 4 Classroom experiment configuration with 24 subjects

The group of 24 subjects, as well as one back up, all received an 18 page briefing guide. They were trained in two days by going to a one-hour briefing and two hours of on-line flying time with Freesim. The first hour was used for familiarisation with ASAS by aiming at conflicts instead of avoiding them. The second hour was used for normal flight training, using ASAS to avoid conflicts but also to fly as efficiently as possible regarding time and fuel.

There were two types of scenarios: ‘normal’ flights and the complex geometries, in this case a circular superconflict with 12, 14 or 24 aircraft (see figure 1).

The experiment consisted of two sessions of four to five runs on two consecutive days. Three runs per day of about 25 minutes consisted of ‘normal’ flights in two traffic densities: low, equal to 1.5 times the reference Western European density [10] and high, equal to 3 times the reference density. The piloted aircraft were set-up in such a way that they would meet under different horizontal aspect angles as well as some vertical conflicts (see figure 5 for an example). Scenarios consisted of about 700 aircraft in upper airspace. Each normal scenario lasted 25 minutes. Subject flew at an altitude of 25,000 ft.

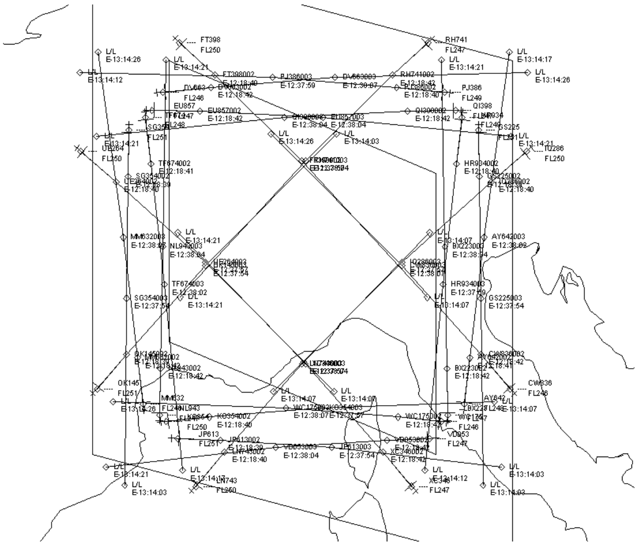

Figure 5 Example scenario for piloted aircraft (background traffic controlled by bots not shown)

During the normal runs half of the pilots were instructed to give flying on time the highest priority, while the other half were instructed to give passenger comfort and safety the highest priority.

After the normal runs one or two superconflict scenarios were flown each day.

Data logging consisted of all conflict data and resolution manoeuvres performance data as well as questionnaires with a NASA Task Load Index (TLX) rating [11] and general comments.

Results

During the normal runs, pilots had no difficulty with airborne separation assurance. Earlier trials showed that pilots tend to solve conflicts horizontally, but this experiment showed that with sufficient training pilots will prefer the, in general more optimal, vertical solution. The scenarios were designed to result in 3 to 4 human-human conflicts per pilot per run. During the experiment this was much lower for two reasons: (1) in most cases the subjects tended to anticipate conflict alerts using the conflict prevention system (2) solving bot-conflicts earlier on sometimes prevented later conflicts.

Table 1 shows the actions used in solving human-human conflicts. Clearly, the vertical speed resolution was used most often. Since this manoeuvre can solve conflicts very quickly a high number of single-sided conflict resolutions occur. In these cases the pilot who was the first to react solved the conflict completely.

Table 1 Resolution manoeuvres for human/human conflicts

	VS	HDG	SPD	Single side
VS	18	4	2	11
HDG	-	1	0	0
SPD	-	-	0	1

Looking at these manoeuvres in more detail, we can distinguish between manoeuvres during normal flight and during a conflict alert (see figure 6). If we look at the manoeuvres of the two different groups, the ‘time’ group and the ‘safety’ group, we can see a minor, but statistically significant, difference. During normal flight the ‘safety’ group used more vertical speed changes, possibly to anticipate and prevent conflict alerts. During conflict alerts the ‘time’ group uses more speed changes.

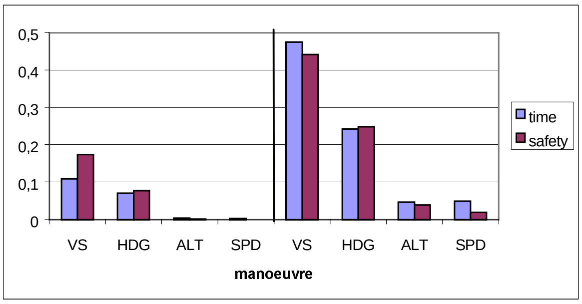

Figure 6 Manoeuvre types for normal scenario both in no conflict situation (left) and in conflict situation (right) for both subject groups

A similar analysis of the manoeuvres in the superconflict scenario is shown in figure 7. Here we can see that the distribution of manoeuvres during a conflict alert or without a conflict alert is nearly the same. This is probably caused by a higher amount of preventive manoeuvres.

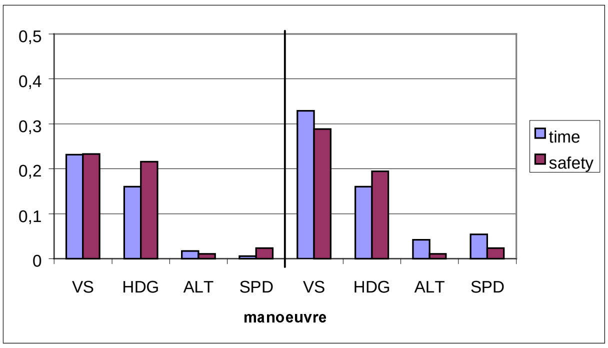

Figure 7 Manoeuvre types for superconflict scenarios for both in no conflict situation (left) and in conflict situation (right) for both subject groups

The superconflict scenarios that were used for the experiment were extreme situations with 12, 14 or 24 aircraft. The bots cannot solve these scenarios without scraping each other’s protected zone (intrusions < 10%). Similar effects occur with human pilots. In the table below the intrusions have been listed together with the average number of conflicts per aircraft.

Table 2 Intrusion logged during extreme superconflicts

	No. intrusions	Mean intrusion time [s]	Conflicts/ aircraft (STD)
Super24			
Bots	32	17.8	12.1 (2.3)
Pilots	31	18.7	7.6 (3.4)
Super14			
Bots	13	18.3	9.8 (2.5)
Pilots	14	15.8	5.5 (2.3)
Super12			
Bots	3	13.3	8.8 (2.0)
Pilots	9	17.1	5.2 (3.1)

We can see that the number of intrusions is not so different between pilots and bots (except for the 12 aircraft superconflict). Looking at the number of conflicts per aircraft, we can see a statistically significant difference: pilots have a lower number of conflicts per aircraft.

The post-run TLX rating from the questionnaires has been listed in Table 3. The difference between the low and high traffic density TLX rating did not reach statistical significance ($p<0.10$), but between the normal and super conflicts it was highly significant ($p<0.001$).

Table 3 TLX rating per scenario

Type of scenario	TLX rating (on 10 point scale)
Normal low density	1.42
Normal high density	2.04
Superconflicts	4.58

Clearly the ratings of the normal scenarios were low on the overall scale of 10. The performance and temporal workload were rated higher during superconflict scenarios. The subject pilots also commented that airborne separation assurance was not as 'exciting' as they thought it would be.

Discussion

The web experiment shows that it is technologically feasible to run a simulation of Free Flight over the internet. It also shows some potential disadvantages, which require extra attention during the organisation of internet trials: training and commitment of the participants.

During the web experiment, pilots could not distinguish between traffic controlled by bots and by humans, so the pilot models passed this variation of the Turing-test. This shows that the off-line simulations are a useful validation, even though at that time the bots were not able to use the conflict prevention module of ASAS. This functionality has been added later.

The web experiment also showed how different the same scenario could be experienced by different aircraft. In general, the average conflict rate per aircraft is less important than how many aircraft will experience a conflict rate that is too high. Traffic flow management should be able to predict and prevent this. To investigate how predictable this is, more traffic simulations, on-line and off-line, are required.

The low TLX ratings of the classroom experiment confirm the results of earlier experiments [8] in which a low workload was found. There was no loss of separations except for two bots, which started a descent causing an immediate loss of separation. This was because they had no conflict prevention module in their ASAS at that time.

The results show that procedures or company directives do have an effect. During training the importance of first trying the vertical resolution was stressed. It can be seen that when flying level, pilots used the vertical manoeuvre. During the climb or descent, they tended to use the horizontal manoeuvre more often than when flying level. The effect of flying very efficient, and more aggressive, versus flying very safely, and more cautious, is statistically significant but minor. Considering the controlled environment of the experiment, the effect could still be worse in real life.

The extreme superconflicts of 12, 14 and 24 aircraft were flown with some losses of separation although all of them infringed less than 10% of the protected zone. Looking at the number of conflicts, humans proved to be better at preventing conflicts in these extreme scenarios. This means that when validating bottleneck scenarios with off-line traffic simulations using the traffic manager the outcome can be regarded as a conservative estimate: in real life humans will probably do better.

The single sided conflict resolutions show that the co-operative approach could erode if everybody uses vertical conflict resolutions. Because the vertical conflict resolution is not only efficient, with respect to fuel and time, but also very effective and quick, it might lead to 'playing chicken': waiting for the other aircraft to react. Currently NLR looks at two ways of solving this: (1) showing only a 50% vertical solution during the amber conflict alert (2) using a priority & co-operative system in combination with an optional voltage potential resolution. This last solution allows both aircraft to manoeuvre, even though only one is expected to solve the conflict during the amber conflict alert.

Conclusion

The simulation configuration consisting of the Traffic Manager as host and the network of Freesim flight simulation programs has proven to be technologically feasible in both an internet and local area network environment. This unique set-up is extremely useful for the investigation of larger scale issues that can not be investigated by one or a limited number of research flight simulators. Web experiments however require tight control over training and participation.

The traffic simulations with the pilot models, or bots, implemented in the Traffic Manager provide an adequate, but somewhat conservative, picture of human piloted traffic. Humans are better at anticipating conflicts, which helps solving bottleneck scenarios, despite individual differences, which are absent in the bots.

Directives or procedures, given by rule makers and/or companies, do have an effect on the way conflicts are solved on a micro-scale. The robustness of airborne separation assurance seems to prevent any noticeable macro-scale effects. Competitive effects did not have an observable effect on the overall traffic pattern in these experiments.

To avoid erosion of a co-operative concept, clear rules about when somebody is required to take action are required. Two potential alternative concepts are proposed here: (1) A 50% solution is provided in low to medium urgency conflict alerts. (2) A combination of a priority/co-operative concept where the low-medium urgency conflict alerts are treated as priority conflicts, even though the resolution advisories allow co-operative manoeuvring, for instance for bottleneck scenarios. Maintaining the robustness and ability to handle bottlenecks is important when changing the co-operative rules.

Even in high densities during normal scenarios the pilot workload is relatively low. Only in bottleneck scenarios, like the circular superconflict, is there an increase in workload, though this is still low on the overall scale.

An important parameter for airborne workload and the acceptability of airborne separation assurance appears to be the conflict rate distribution over aircraft. Further research should focus on the predictability and manageability of the number of aircraft with peak conflict rates.

Acknowledgement

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Abbreviations

ADS-B	Automatic Dependent Surveillance – Broadcast
ASAS	Airborne Separation Assurance System
ATC	Air Traffic Control
ATM	Air Traffic Management
CD	Conflict Detection
CD&R	Conflict Detection and Resolution
CDR&P	Conflict Detection, Resolution and Prevention
CDTI	Cockpit Display of Traffic Information
CP	Conflict Prevention
CR	Conflict Resolution
EFIS	Electronic Flight Instrument System
FAA	Federal Aviation Administration
FF	Free Flight
FFAS	Free Flight Airspace
FMS	Flight Management System
NASA	National Aeronautics and Space Administration
ND	Navigation Display
NLR	National Aerospace Laboratory, The Netherlands
PASAS	Predictive ASAS (sometimes abbreviated as PredASAS)
PFD	Primary Flight Display
RLD	Rijksluchtvaartdienst (Dutch CAA)
RSME	Rating Scale of Mental Effort
RTCA	Radio Technical Commission for Aeronautics
STD	Standard Deviation
TLX	Task Load indeX
TMX	Traffic Manager (=TEM)

Keywords

Free Flight, Airborne Separation Assurance, ATM, ATC, CDTI, simulation, distributed simulation, workload, conflict detection, conflict resolution, ASAS, ADS-B

Biographies of the authors

Jacco Hoekstra graduated in 1991 from the Delft University of Technology, Faculty of Aerospace Engineering. He joined NLR at the Flight Simulation department and worked on a number of human factors studies, among others Controller Pilot Data Link and Free Flight. In 1998, he transferred to the human factors department. In the fall of 2001 he obtained the doctoral degree at Delft University of Technology on the conceptual design of Free Flight. Dr. Hoekstra is also the head of the Civil Aviation group that is a part of the Human Factors department.

Ronald van Gent has studied aeronautical engineering at the Delft University of Technology where he received his MSc in 1987. After that he has been working in the area of Human Factors, first at TNO in Soesterberg, later in Amsterdam at the NLR. Main projects he was involved in were pilot-controller datalink studies and the Free Flight studies.

Jaap Groeneweg graduated in 1989 from the Delft University of Technology, Faculty of Aerospace Engineering. He joined NLR at the Flight Simulation department and worked on the development of the research flight simulation configuration. In 2000, he transferred to the human factors department where he works as project manager.